AD-A235 577

PL-TR-91-2028

(2)

Seismic Event Location at Regional Distances

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22 March 1991

Final Report
22 July 1988 - 14 January 1991

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PHILLIPS LABORATORY
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Defense Advanced Research Projects Agency
Nuclear Monitoring Research Office
ARPA ORDER NO. 5299

MONITORED BY
Phillips Laboratory
F19628-88-K-0037

This technical report has been reviewed and is approved for publication.

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FOR THE COMMANDER

FOR: DONALD H. ECKHARDT, Director
Earth Sciences Division

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
22 March 1991

3. REPORT TYPE AND DATES COVERED
Final 22 Jul 88-14 Jan 91

4. TITLE AND SUBTITLE
Seismic Event Location at Regional Distances

5. FUNDING NUMBERS
F19628-88-K-0037
PR 8A10
TA DA
WU AI

6. AUTHOR(S)
C. Thurber

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Research Foundation of SUNY
P.O. Box 9
Albany, NY 12201

8. PERFORMING ORGANIZATION REPORT NUMBER
431-6722A-2

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Phillips Laboratory
Hanscom AFB, MA 01731-5000

DARPA
1400 Wilson Blvd
Arlington, VA 22209-2308

Contract Manager: James Lewkowicz/LWH

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
PL-TR-91-2028

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release;
Distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Three-component data from regional seismic events recorded by the former NRDC-Soviet Academy of Sciences regional seismic network in Kazakhstan, USSR, have been analyzed with the primary goal of improving regional seismic event location capability. Data from these events were used in the investigation of the following problems related to regional event location: 1) determination of wave arrival azimuth; 2) observability and value of secondary phase arrivals; 3) evaluation and improvement of regional event location algorithms; 4) independent determination of "master event" locations. Starting with very little prior information, we have demonstrated the potential for a sparse seismic network of three 3-component stations to locate events over a wide region with reasonable accuracy and precision, both for epicenter and depth. Our basic findings are: that arrival azimuth can be determined with reasonable precision, but the data provide little in the way of location constraint in most cases; secondary phase arrivals are routinely observable over a wide distance range, and they provide important location constraints; existing location algorithms perform well and provide appropriate estimates of location uncertainty, but must be modified for far-regional applications; numerous "master events" have been identified and utilized to improve our location capability.

14. SUBJECT TERMS
Event location, regional seismic waves, satellite imagery, depth determination

15. NUMBER OF PAGES
40

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

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1. Summary

We have carried out a detailed analysis of three-component data from regional seismic events recorded by the former NRDC-Soviet Academy of Sciences regional seismic network in Kazakhstan, USSR, with the primary goal of improving regional seismic event location capability. The data from these events were used in the investigation of the following problems related to regional event location: 1) determination of wave arrival azimuth; 2) observability and value of secondary phase arrivals; 3) evaluation and improvement of regional event location algorithms; 4) independent determination of "master event" locations. Starting with very little prior information, we have demonstrated the potential for a sparse seismic network of three 3-component stations, with an aperture of about 400 km, to locate events over a wide region with reasonable accuracy and precision, both for epicenter and depth. Our basic findings are: that arrival azimuth can be determined with reasonable precision, but the data provide little in the way of location constraint in most cases; secondary phase arrivals are routinely observable over a wide distance range, and they provide important location constraints; existing location algorithms perform well and provide appropriate estimates of location uncertainty, but must be modified for far-regional applications; numerous "master events" have been identified and utlilized to improve our location capability. Some keys to the success of this effort have been: (1) the initial availability of an adequate crustal model, coupled with the inferred modest level of lateral variations in crustal structure within the array; (2) the availability of data from known sources (the 1987 chemical explosions) to aid the calibration of travel time models; (3) the existence of identifiable secondary P arrivals; (4) the availability of satellite imagery to confirm the source location of some events; (5) the ability to pursue a multifaceted approach to the investigation of the overall location problem (empirical, theoretical, observational). We can make several specific recommendations for future efforts related to regional event location: (1) employ array studies to help identify and characterize secondary regional phases; (2) use short time windows at the onset of the P arrival for precise azimuth estimation; (3) obtain total coverage of the region in question by satellite imagery - including multiple sources of data (e.g., SPOT, LANDSAT). Overall, we regard regional seismic event location to be a difficult but quite tractable problem.

2. Accomplishments

2.1. Task Objectives

We have carried out a detailed analysis of three-component data from regional seismic events recorded by the former NRDC-Soviet Academy of Sciences regional seismic network in Kazakhstan, USSR, with the primary goal of improving regional seismic event location capability. One basic task was the cataloging of locations for some of the regional events detected by the network. The data from these events were used in the investigation of the following problems related to regional event location: 1) determination of wave arrival azimuth; 2) observability and value of secondary phase arrivals; 3) evaluation and improvement of regional event location algorithms; 4) independent determination of "master event" locations. An improved model for the regional seismic velocity structure was sought in conjunction with the above tasks.

2.2. Technical Problem

Seismic event location remains a fundamental component of monitoring efforts related to verifying nuclear test ban or test limitation treaties. Event location is important both as a basis for discrimination by itself and as a starting point for the analysis of wave propagation and attenuation. The earthquake location problem is relatively well understood on a theoretical basis (Thurber, 1986). However, it can be expected that event location will be a non-trivial problem for in-country regional networks like those considered in the recent literature (e.g., Evernden et al., 1986).

Valuable experience in the study of regional wave propagation in the U.S. has been gained from the operation of the Regional Seismic Test Network (RSTN), but the direct applicability of that experience to the regional monitoring of weapons testing in the U.S.S.R. is questionable, due to significant differences in crustal structure and attenuation characteristics. However it is now possible to obtain high-quality digital data from stations within the Soviet Union. An agreement between the National Resources Defense Council, Inc., and the Academy of Sciences of the U.S.S.R. led to the establishment of a three-station seismic network in the spring of 1987 in eastern Kazakhstan in the Soviet Union. Each station consisted of several sets of 3-component instruments, recorded digitally at 250 samples per second per channel using a triggered system (Berger et al., 1988). As part of the agreement, a similar network was set up in the western U.S. The stations of the two networks encircled the Kazakhstan and Nevada nuclear test sites (KTS and NTS), respectively, at distances of about 200 km. The stated purpose of these networks was to collect data relevant to seismic monitoring of nuclear weapons tests (Berger et al., 1987). In late

1988, the Kazakh network was dismantled, and new stations were set up (at much greater distances from KTS) through an agreement established by with the Incorporated Research Institutions for Seismology (IRIS) and the U. S. Geological Survey.

Due to the sparseness of the Kazakhstan network, most regional events (predominantly mining blasts) did not trigger all three stations, and often triggered only one. Similar detection difficulties can be expected for any sparse regional monitoring network. Standard earthquake location algorithms that use P and S wave arrival times alone cannot be expected to yield satisfactory results under such conditions, particularly for small to moderate sized events. Alternative methods and/or additional data are needed for adequate constraint of event locations.

2.3. General Methodology

A promising approach to the problem of locating seismic events with a sparse regional network is the use of arrival times from multiple regional phases (P_g, L_g and R_g, and possibly P^*, S^*, in addition to P_n, S_n) and arrival azimuths. Bratt and Bache (1988) describe an earthquake location algorithm that uses arrival times and azimuths to estimate regional event locations. Secondary arrivals are handled computationally exactly the same as first arrivals. Arrival azimuth information can be incorporated by adding azimuth residuals to the residual vector and the corresponding rows of partial derivatives to the Jacobean (Bratt and Bache, 1988). The partial derivatives for azimuth are derived directly from the source-receiver geometry. Bratt and Bache (1988) applied their algorithm successfully to array data from NORESS and FINESA for events at distance ranges of 200 to 1500 km. Magotra et al. (1987) and Ruud et al. (1988) describe single-station approaches using arrival times and azimuths (slowness vectors) that are conceptually similar to the Bratt and Bache approach. They applied their methods to data from single-site RSTN and NORESS three-component records, respectively.

The standard earthquake location method iteratively solves a matrix equation relating hypocenter adjustments to arrival time residuals via the Jacobian matrix, consisting of the partial derivatives of arrival time with respect to the event coordinates and origin time (Thurber, 1986), with the iterations stopping when some convergence criterion is reached. Arrival azimuth information can be incorporated as additional information for determining the location by adding azimuth residuals to the residual vector and the corresponding rows of partial derivatives to the Jacobian matrix (Bratt and Bache, 1988). The partial derivatives for azimuth are derived directly from the source-receiver geometry. Both the event depth and origin time are independent of the azimuth. In the algorithm TTAZLOC (Bratt and Bache, 1988), the final solution is obtained using iterative damped least squares. The estimate of location uncertainty is derived using a combination

of *a priori* and *a posteriori* data uncertainties (Jordan and Sverdrup, 1981). The *a priori* uncertainty can incorporate estimated uncertainties due to measurement error and inexact knowledge of velocity structure (Bratt and Bache, 1988; Pavlis, 1986). In this initial investigation, we use the estimated uncertainties in arrival time reading and arrival azimuth determination for the *a priori* values. The former typically are 0.25 s for P and 0.5 s for S arrivals, based on subjective estimation of reading quality, while the latter are on the order of 5°, based on the standard deviation of the computed arrival azimuth within the selected window. We also assume a value for the Bayesian parameter K of 8 (Jordan and Sverdrup, 1981). A value for K of 8 asigns 8 degrees of freedom to the *a priori* uncertainty, and implies an expected standard deviation of the *a posteriori* standard deviation variable (the reciprocal of the normalized *a posteriori* uncertainty) of 25% about a mean of 1.0 (Jordan and Sverdrup, 1981). Note that in the discussion and tables, all error ellipses will be represented by the major axes of the 90% confidence ellipses.

A crustal model is required to compute travel times of the various phases. Fortunately, Soviet Deep-Seismic-Sounding (DSS) surveys have been carried out in the region, including one line just to the west of Karkaralinsk (Figure 1), yielding estimates of crust and upper mantle P velocities and crustal thickness. Results from these profiles are summarized by Belyaevsky et al. (1973), Antonenko (1984), and Leith (1987). Crustal thickness varies between about 45 and 55 kilometers in the immediate vicinity of the network (Belyaevsky et al., 1973). We have adopted a layered approximation to the P-wave velocity model reported by Antonenko (1984), shown in Figure 2, modified to account for the low-velocity granites that underly the station sites (Leith, 1987). The model predicts a P_n crossover distance of about 220 km.

There is little published information on the S velocity structure in the region. Priestley et al. (1988) carried out a preliminary teleseismic waveform inversion for records at stations BAY and KKL using the method of Owens et al. (1984), deriving a layered model for the S velocity structure beneath those stations. For comparison, taking the DSS profile results and assuming a constant V_p/V_s ratio of 1.73 gives values for V_s that are consistent with the teleseismic waveform analysis of Priestley et al. (1988) for the upper crust, but somewhat lower than Priestley's for the lower crust. This is in agreement with the finding of Alekseev et al. (1988) that V_p/V_s is higher in the upper crust than the lower crust in the area of Kazakhstan near the Tien Shan. Given the uncertainties, however, we have chosen to calculate the event locations using two different S velocity models (Table 1), one with constant V_p/V_s ratio (Model A), and another using the model of Priestley et al. (1988) (Model B).

The location algorithm TTAZLOC is structured to be able to utilize arrival times of secondary phases, assuming they can be identified and modeled correctly. Travel time calculations

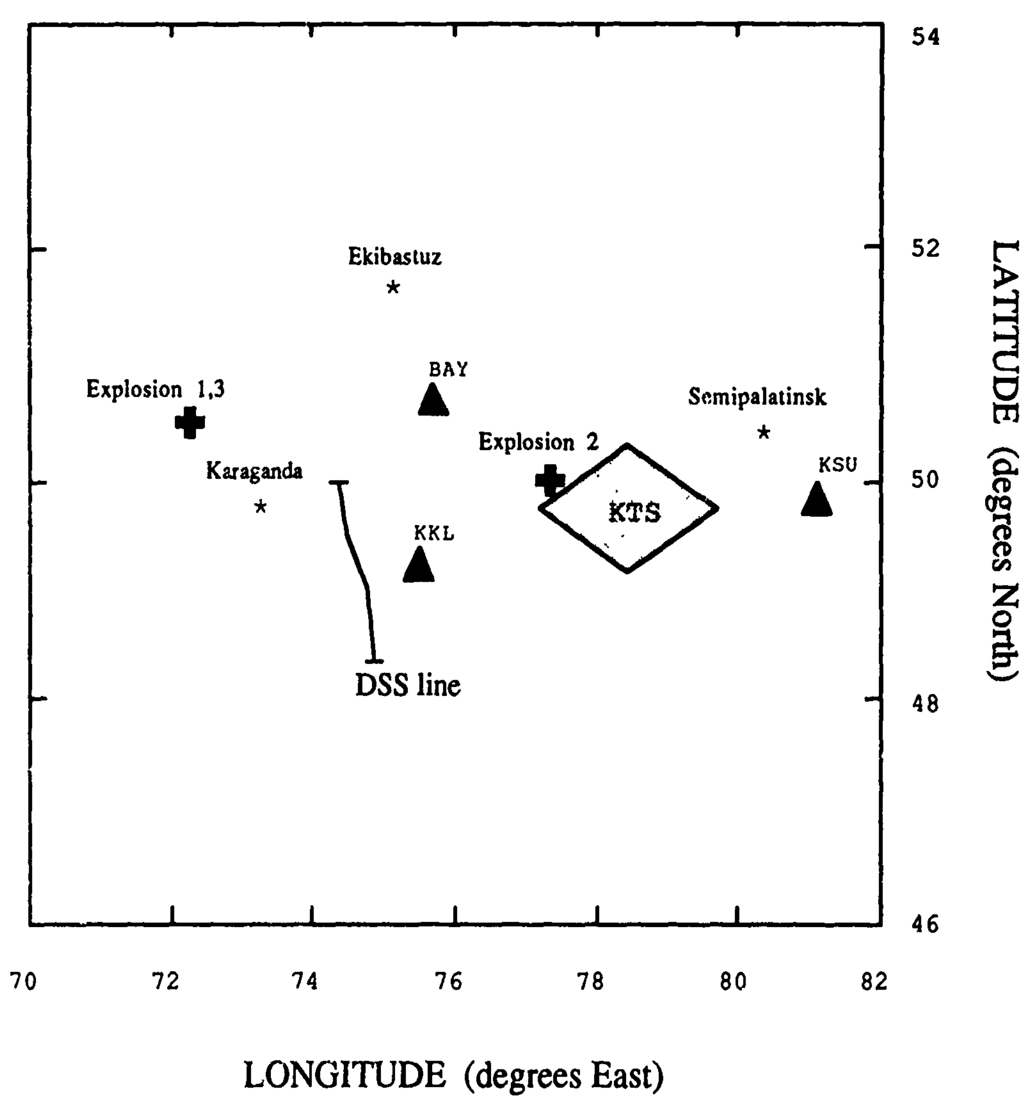

Figure 1. Configuration of the NRDC-Soviet Academy seismic network, located near the Kazakhstan Test Site (KTS) on the steppes of Central Asia. Stations BAY, KKL, and KSU are indicated by the solid triangles. Also shown are the sites of the September 1987 chemical explosions (+) and the location of a Deep-Seismic-Sounding profile (DSS).

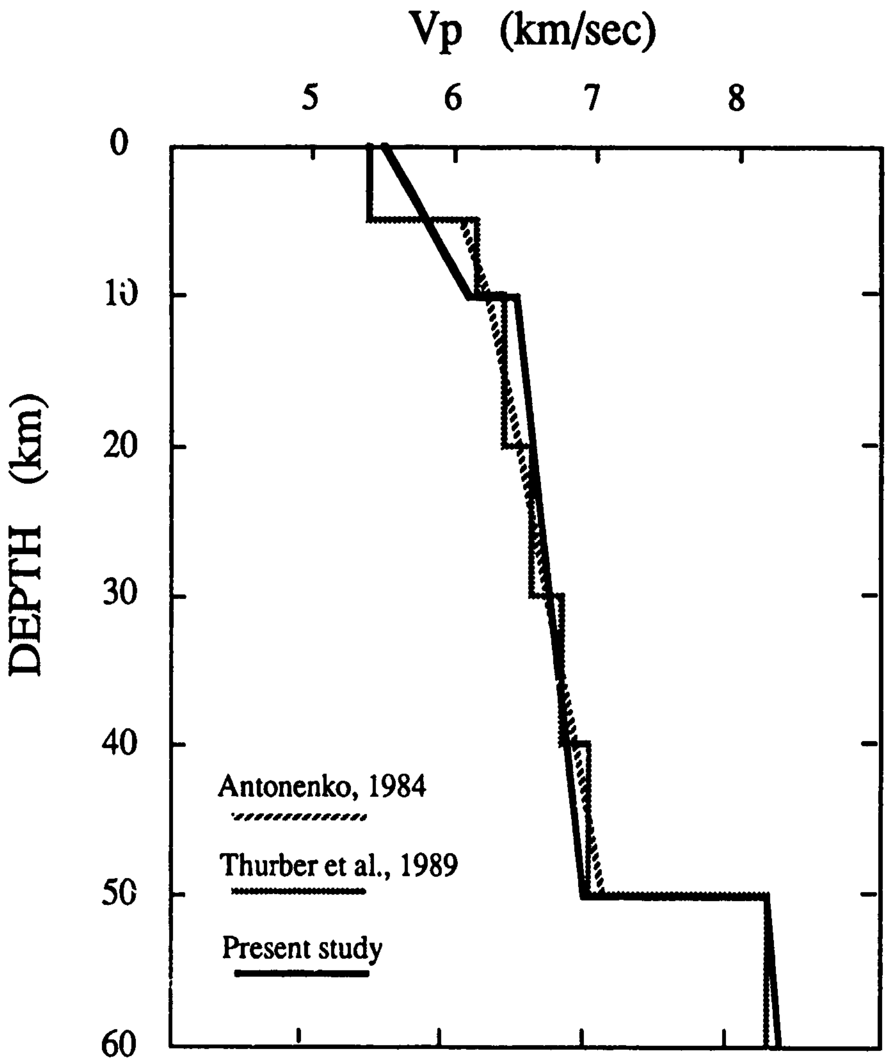

Figure 2. Comparison of the 1-D velocity model for the Kazakhstan area from Deep Seismic Sounding (Antonenko, 1984), and its modifications based on empirical location work, mostly based on the 1987 chemical explosion (Thurber et al., 1989) and synthetic modeling of regional seismograms (this work).

Table 1

Velocity models used for event location

MODEL A

Depth range (km)	Vp (km/sec)	Vs (km/sec)
0 - 5	5.40	3.05
5 - 10	6.15	3.50
10 - 20	6.35	3.60
20 - 30	6.55	3.70
30 - 40	6.75	3.85
40 - 50	6.95	3.95
50 +	8.20	4.65

MODEL B

Depth range (km)	Vp (km/sec)	Vs (km/sec)
0 - 5	5.40	3.30
5 - 10	6.15	3.40
10 - 20	6.35	3.50
20 - 30	6.55	3.70
30 - 40	6.75	4.10
40 - 50	6.95	4.30
50 +	8.20	4.70

for the P velocity model in Figure 2 indicate that an upper-crustal refraction along the 6.35 km/sec layer at 10 km depth gives the first arrival from surface sources in the distance range of about 100 to 220 km, and also suggests it might produce a significant secondary arrival beyond that distance. We will denote this phase as P_g, following the notation of Aki and Richards (1980; p. 213). The phases we use for locations include P_n, P_g, S_n, and S_g, when observable; we have not used L_g, as we regard it as having a less precisely measurable arrival time.

For seismic arrays or sparse networks, the azimuth of arriving phases can provide crucial constraints for determining event locations. We determine arrival azimuths using a method similar to that described by Magotra et al. (1987) for estimating the polarization direction of arriving seismic phases. For a polarized signal in the presence of noise, the eigenvector corresponding to the largest eigenvalue of the covariance matrix for the signal components gives the direction of polarization, and the ratio of eigenvalues measures the rectilinearity of particle motion (Kanasewich, 1981). Since we are interested just in the arrival azimuth, the horizontal component seismograms from a station are windowed (usually over 100 to 250 samples or 0.4 to 1.0 s) and demeaned, and the 2-by-2 signal covariance matrix C is computed:

$$\mathbf{C} = \begin{bmatrix} \mathrm{Var[NS]} & \mathrm{Cov[NS,EW]} \\ \mathrm{Cov[NS,EW]} & \mathrm{Var[EW]} \end{bmatrix}$$

where NS and EW represent the north-south and east-west component time series, respectively. From the eigenvector for the largest eigenvalue of C, $E_{\lambda max} = [\, e_1 \;\; e_2 \,]$ the polarization direction ϕ for the time window can be computed from $\tan\,\phi = e_2 / e_1$. For the P-wave, ϕ will be the apparent back-azimuth to the event. The inherent 180° ambiguity in azimuth can be resolved by using all three components of particle motion (Magotra et al., 1987). We find we are consistently able to determine azimuth estimates from the first P arrival, usually with an estimated uncertainty of 5° or less. Particle motion plots are also examined for a simple check of the results.

Our methodology for evaluating the utility of secondary arrivals and arrival azimuths for the purpose of regional seismic event location has been to approach the issue from several complementary directions to seek self-consistent results. These directions are observational, empirical, and theoretical. Observationally, we have examined and analyzed regional seismic data from the Kazakhstan area to investigate the quality of secondary phase and arrival azimuth data. Empirically, we have assessed the ability to determine accurate event locations in cases where the true event location is known independently or can be inferred, for example from satellite images. Theoretically, we have evaluated extensively the formal regional event location uncertainty using secondary phase and arrival azimuth data in conjunction with the traditional first arrival data. Overall, we feel we have developed a consistent picture of regional event location capability, but

one which leaves room for improvement as our data and our understanding of regional wave propagation improves.

2.4. Technical Results

The project duration was approximately 30 months, 7/22/88 to 12/31/90. Our efforts during the period were divided among four components of study: arrival azimuth, secondary arrivals, location algorithm, and master events. Progress achieved in these four project components is described in the following sections.

2.4.1. Arrival Azimuth

A number of investigators have examined methods for arrival azimuth determination from 3-component seismic data (Magotra et al., 1987; Jurkevics, 1988; Christoffersson et al., 1988). We have found the principal components analysis method to be quite successful, particularly for broadband data analyzed in short time windows. Figure 3 shows an example of arrival azimuth estimation using principal components analysis. The data are from the 1987 chemical explosion 1 in Kazakhstan recorded at station KKL (Given et al., 1990). The arrival azimuth and rectilinearity are calculated from the horizontal components, using a sliding time window of 0.4 seconds. No filtering (Jurkevics, 1988) or time-lagged weighting (Magotra et al., 1987) is applied. Note the significant increase in rectilinearity and stability of the azimuth estimate associated with the regional seismic phases identified in the seismogram. A reanalysis of several other selected events from the NRDC data set provides clear justification for the use of short, early windows in the P waveform for computing arrival azimuth. This strongly suggests that automated algorithms for estimating arrival azimuth should use one or more polarization strength measures to select an appropriate window for computing an azimuth estimate.

A comparison was also made between time-domain (principal components) and frequency-domain (multiple spectral taper) polarization techniques for determining arrival azimuth from the chemical explosion data. Our work has shown that the two methods obtain compatible results for matching time windows. However, the time-domain method has the advantage of finer time resolution, allowing identification of scattered and/or converted waves in the coda of the desired direct arrival. The frequency-domain method is useful for indicating the bandwidth over which reliable azimuth information is present (usually 1 to 15 Hz).

Two critical questions are (1) what are the accuracy and precision of arrival azimuth estimates, and (2) how useful is arrival azimuth in constraining regional event locations. We have

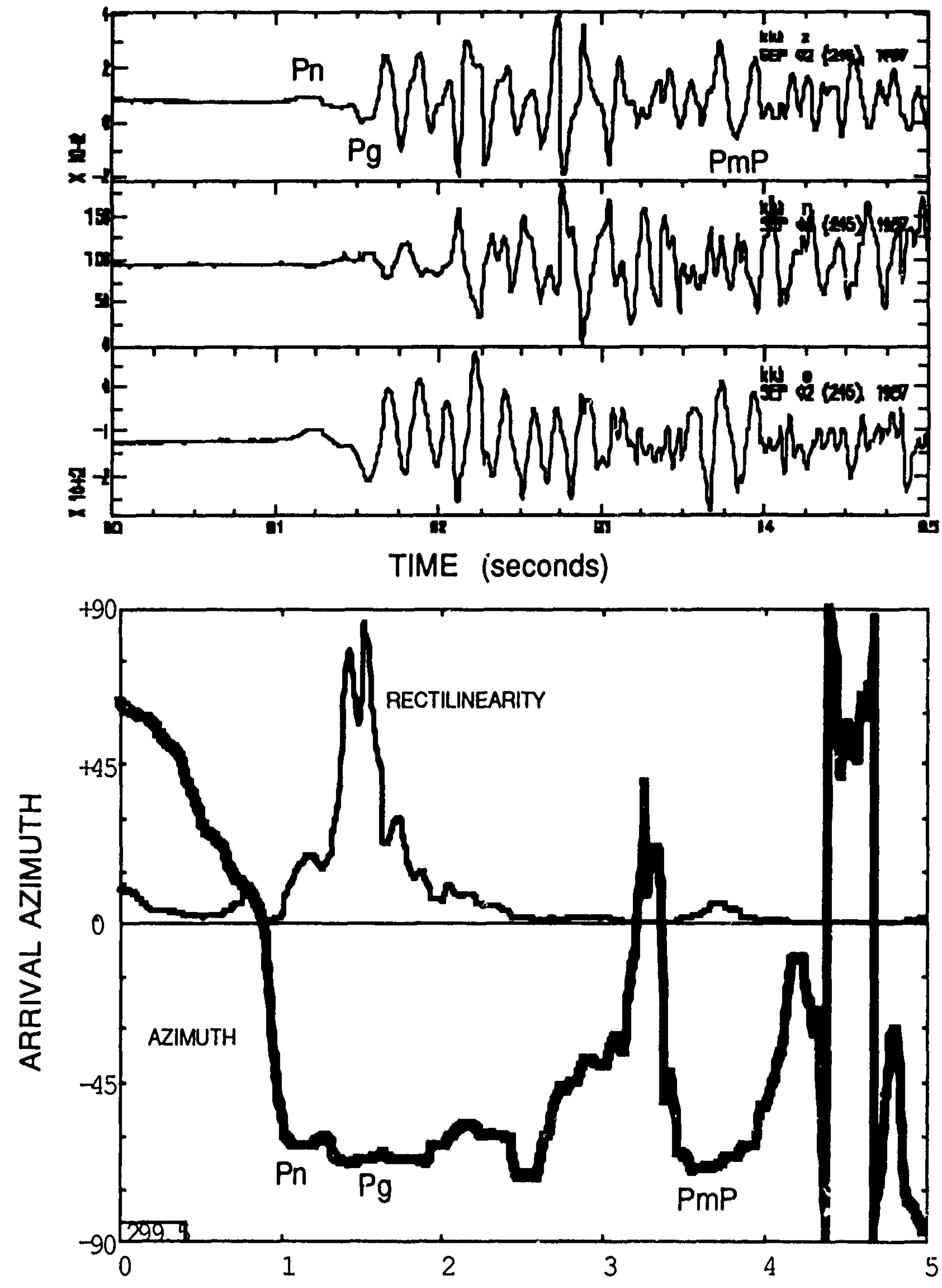

Figure 3. Arrival azimuth estimation using principal components analysis. The top panel shows 5 seconds of the 3-component seismograms from Chemical Explosion 1 recorded at station KKL, while the bottom panel shows the calculated arrival azimuth and rectilinearity of the horizontal components, using a sliding time window of 0.4 seconds.

Table 2

Estimated and true arrival azimuths for 1987 Kazakhstan chemical explosions 1 and 2

Explosion		BAY	KKL	KSU
1	Estimated (± 1 σ)	255 ± 2	293 ± 1	276 ± 2
	True	257	296	277
	Error	2	3	1
2	Estimated (± 1 σ)	121 ± 2	56 ± 2	279 ± 4
	True	125	61	272
	Error	4	5	7

limited answers to the first question, and a fairly complete answer to the second. Our analysis of data from the 1987 chemical explosions in Kazakhstan suggests that azimuth accuracy is on the order of 5° and that precision is no better than 2°, on average (see Table 2 above). However, the latter estimate is not based on a formal error assessment, rather on an evaluation of azimuth stability within the selected time window. Other studies have suggested that precision is only 5 to 10°.

Regarding constraining regional event locations, our empirical and theoretical analyses demonstrate the limited utility of azimuth data. For single-station locations, of course, arrival azimuth provides the only information about source direction, and thus is critical. However, only very poor constraint on epicenter is obtainable if the azimuth uncertainty is on the order of 5°; uncertainty increases roughly linearly with epicentral distance, at a rate of about 0.1 km per km. Thus single-station location uncertainty will be quite high at regional distances (200 to 2000 km, say). This situation can be improved significantly only if the uncertainty in azimuth estimation can be reduced substantially, for example with the use of arrays and the correction for systematic errors.

For two-station locations, azimuth data contribute only to a slight reduction in epicenter uncertainty, specifically along the line connecting the two observing stations, and contribute nothing to reducing depth uncertainty. We do note, however, that without azimuth data, there is a fundamental ambiguity in source location in this case - two points symmetrically located about the line connecting the two observing stations will always fit the arrival time data equally well. Azimuth information can readily remove this ambiguity. Thus they are essential for providing

directional information but of themselves do not improve two-station location constraint significantly. We have also determined that arrival azimuth data contribute no significant information in the case of three-station locations.

2.4.2. Secondary Arrivals

One of our fundamental hypotheses at the outset of this study was that secondary arrivals could prove to be extremely useful for constraining regional event locations. We have undertaken a three-pronged approach to the evaluation of this hypothesis: empirical (location results using secondary arrivals), theoretical (quantification of hypothetical location capability with secondary arrivals), and observational (observability of secondary arrivals). Our results appear to be self-consistent and very encouraging regarding the utility of secondary arrivals.

Our most significant empirical results concern the determination of source depth with travel time data. A thorough analysis of data from the 1987 chemical explosions in Kazakhstan has shown that source depth can be adequately constrained even with data from a single station if multiple arrivals are used. We relocated chemical explosions 1 and 2 first with depth fixed at 5 km and then with depth free, using velocity model A. For both events, the fixed 5 km depth solutions were notably worse than the original fixed 0 km depth solutions: the mean absolute arrival time residuals increased from 0.08 sec to 0.87 sec for explosion 1 and from 0.24 sec to 0.68 sec for explosion 2. Furthermore, for the solutions with focal depth left free, the final calculated location was in fact at 0 km depth in each case, with estimated focal depth uncertainties of 0.6 km and 1.3 km for explosions 1 and 2, respectively. If we further eliminate the data from station KSU, the location quality remains essentially unaltered for explosion 1, but degrades significantly for explosion 2. In the latter case, constraint on source depth is completely lost. With data from only a <u>single</u> station (either BAY or KKL), the solution for explosion 1 is still stable and reasonably accurate, falling within 8 km in epicenter and 1 km in depth. We attribute these surprisingly successful results for explosion 1 to the availability of multiple secondary arrivals (P_g and S_n). These stations lie just beyond the crossover distance, where P_n is the first arrival and P_g can be clearly observed following P_n (see Figure 3 for an example). Thus we would agree with the claim of Ruud et al. (1988) that focal depth can be determined from data at a single station. A far more thorough analysis will be required to establish the conditions under which depths of regional events can be adequately constrained in general.

By making use of inverse theory, it is possible to analyze the expected location uncertainty and stability (including depth) and evaluate the importance of each arrival time datum as functions of actual event location, given the station locations and observed phases. Our theoretical analysis of location capability (Li and Thurber, 1991) applied Singular Value Analysis (Lawson and

Hanson, 1974) to suites of hypothetical arrival time and azimuth observations of P and S phases at the three NRDC network stations (or subsets thereof). Hypothetical sources were distributed over a region 1000 km by 1000 km, with a grid size of 20 km. Source depths were varied between 0 km and 8 km; we find that location capability is quite insensitive to source depth over this range. We calculated the theoretical location uncertainty (assuming reasonable data variance values), and also the data importance, to assess the solution quality for the various suites of data (stations and phases). Arrival time uncertainty of 0.5 s and arrival azimuth uncertainty of 5° was assumed.

Our theoretical results indicate that source depth can be constrained quite well with adequate regional travel time data, with epicenter somewhat less well constrained. First P and first S arrivals alone at the three stations are not adequate for acceptable epicenter and depth constraint. Location uncertainties for both parameters exceed 30 km for half of the study region. However, adding a single secondary P observation, such as PmP, at all three stations results in depth uncertainties less than 10 km and epicenter uncertainties less than 15 km over more than 95% of the region. Figures 4 and 5 provide a summary of theoretical location uncertainty (depth and epicenter) for various combinations of regional phases.

We also carried out the task of evaluating secondary P phase observability from previously studied events recorded by the former NRDC network surrounding the Soviet KTS. PmP is the most readily observed secondary phase over a substantial distance range, perhaps 125 to 300 km. Pg as a secondary arrival probably has only a very limited range of use just beyond the Pn crossover distance, around 230 to 270 km. We can adequately model the arrival times of these phases (Table 3) using only a slight modification of the model adopted in our previous work on event location (Figure 2 above).

Table 3

Misfit of observed P phase times to one-dimensional velocity model

Phase	Mean (sec)	Standard Deviation (sec)
Pg	-0.02	0.4
Pn	+0.05	0.5
PmP	+0.24	0.3

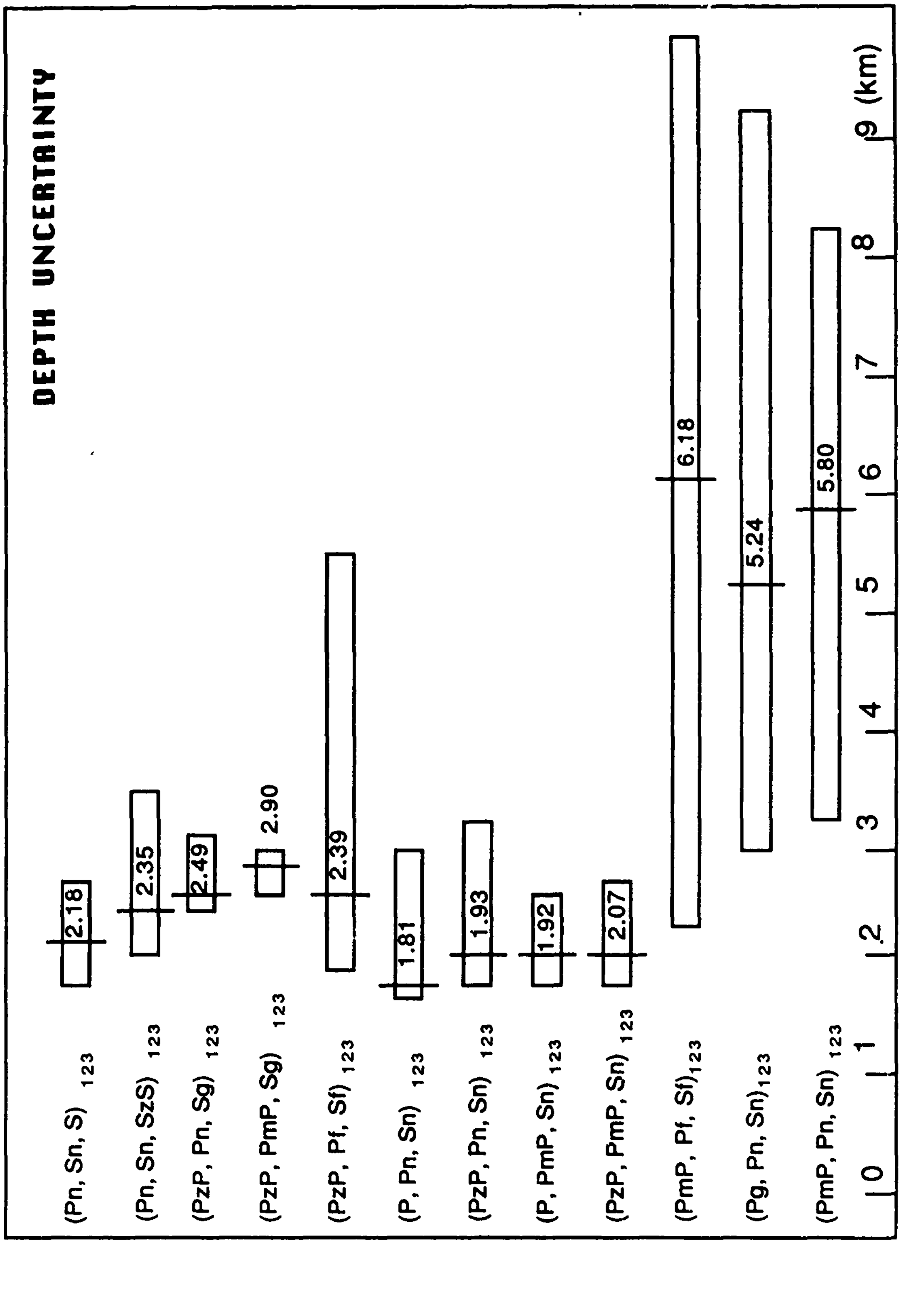

Figure 4. Range (box) and mean (vertical bar) of calculated location uncertainty for event depth for suites of possible regional phase observations at 3 stations.

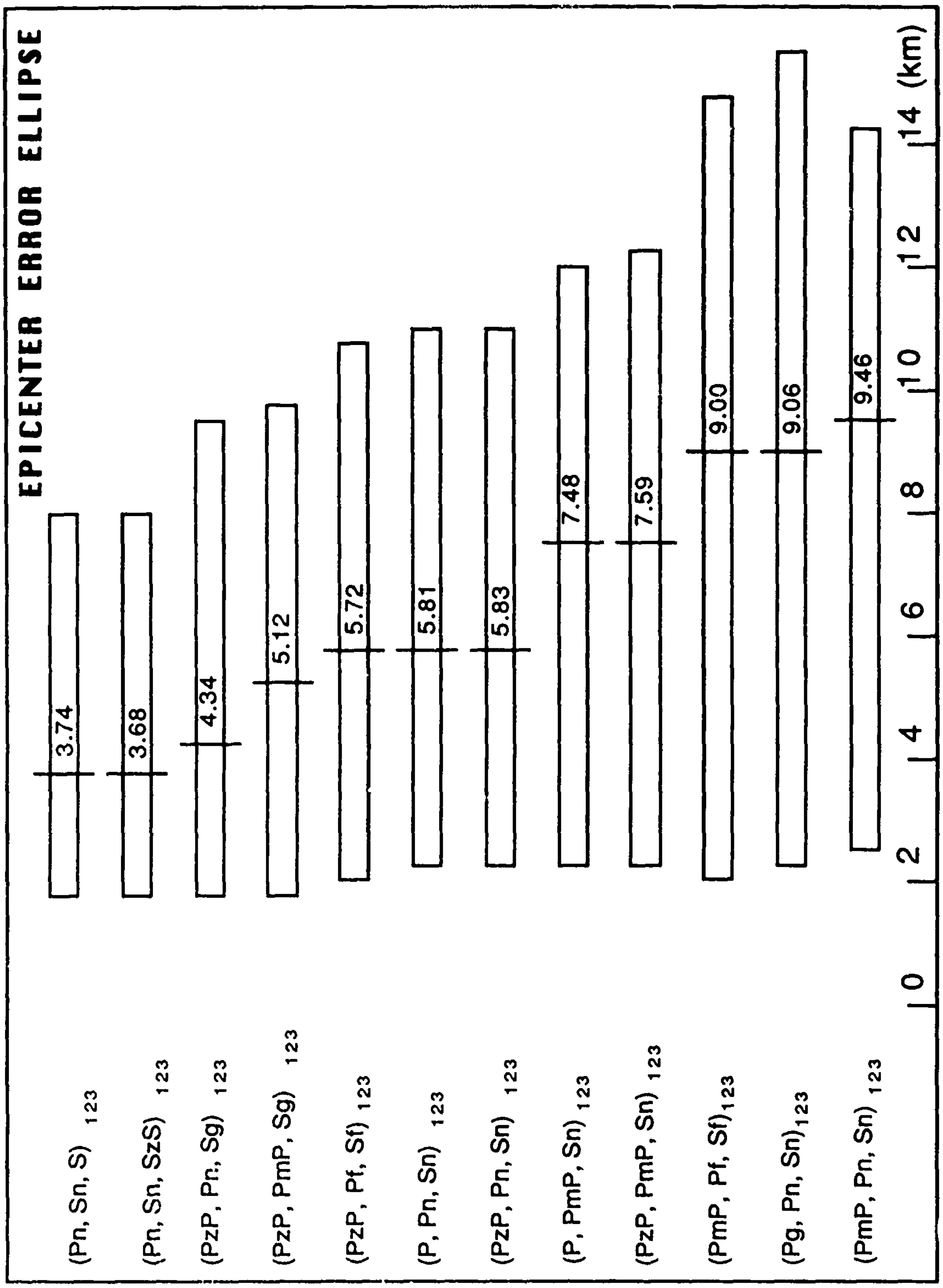

Figure 5. Range (box) and mean (vertical bar) of calculated location uncertainty for event epicenter for suites of possible regional phase observations at 3 stations.

2.4.3. Location Algorithm

A comparison was made between travel time calculations in a flat-layered versus spherical-shell earth model to define the limitations for use of a flat-layered model in regional travel time calculations. Our calculations indicate that the travel time discrepancy increases approximately linearly with distance, increasing from 0.5 seconds at 600 km to 1.8 seconds at 2000 km. Thus it will be essential to determine far-regional event locations using a spherical earth model.

Our previous work on regional event location (Thurber et al., 1989) utilized the location algorithm TTAZLOC, which allows the use of "a priori" information in the assessment of event location uncertainty. For our initial work, it was assumed that errors in determining body wave arrival times were the sole contributor to location uncertainty (data-based uncertainty). We are now examining the self-consistency of our a priori uncertainty estimates with the a posteriori uncertainty estimates. The Bayesian statistics approach used in TTAZLOC apportions the contributions to the a posteriori uncertainty estimates according to a "K-weight": a priori uncertainty is treated as providing K data, and residuals from arrival time and azimuth data provide an additional N observational data. Previous studies have used a K-weight of 8, which would be statistically consistent with a normalized standard deviation of the distribution of the standard deviation variable (the reciprocal of the standard deviation) of 0.25, and of course a normalized mean of 1.0 (Jordan and Sverdrup, 1981). For our previous work assuming the data-based uncertainty values (case a), the standard deviation is 0.24 but the mean is 0.81, 20% too low. If we instead assume fixed uncertainty values (in case b of 0.25 seconds for P, 0.5 seconds for S, in case c of 0.5 seconds for P, 1.0 seconds for S, and 5° for azimuth in both cases) reflecting the assumption that inaccuracies in the crustal velocity structure, rather than the data, control location uncertainty, then we produce distributions with standard deviations of 0.19 and 0.17 and means of 0.97 and 1.04 (cases b and c), very close to the correct mean of 1.0 but now below the self-consistent standard deviation value of 0.25. The main implication is that the study of NRDC data by Thurber et al. (1989) underestimated the location uncertainties of regional events by about a factor of 1.5 to 2, given the present state of knowledge of crustal structure. However, a modest improvement in our ability to predict regional seismic wave travel times (P to 0.25 sec, S to 0.5 sec, for example), would reduce the location uncertainties back to quite low levels.

2.4.4. Master Events

One of the keys to improving event location capability is the availability of "master events" that can be used for "calibration" of travel time models (or equivalently seismic velocity structure

models). We have used a combination of events with independently known location (chemical and nuclear explosions) and events whose source can be identified via satellite images to produce a set of such master events for the NRDC network. Unfortunately, both types of events are quite limited in number, due to the small number of supervised explosions in Kazakhstan to date (four, two at the same site) and the sparsity of high-quality satellite observations available. The chemical explosions proved particularly valuable for a first-order evaluation of the velocity model used for event location (Thurber et al., 1989).

On September 2 and 3, 1987, three large (10 to 20 ton) chemical explosions were detonated in the vicinity of the network, two at the same location to the northwest of Karaganda and one on the western boundary of the Kazakh test site (Eissler et al., 1987). Their locations are indicated in Figure 1. Eissler et al. (1987) described the characteristics of the seismograms and presented basic analyses of their spectra and size. All three blasts were successfully recorded by each of the network stations. However, we have concentrated our analysis on the data for the first two explosions, as records of the third overlapped a teleseismic arrival from a magnitude 7.2 earthquake in the Macquarie Islands. The event depths were fixed at the surface for the initial set of calculations. In the following discussion, it should be kept in mind that the "true" explosion locations may in fact be somewhat in error, perhaps by as much as a few kilometers, as it is not certain how accurate the maps are that were used by the Soviets to provide the locations.

Explosion 1 was located well outside the network, at sufficient epicentral distance from all the stations for P_n and S_n to be clear first arrivals. A strong crustal refracted phase (P_g) is also observed at stations BAY and KKL, both about 250 km from the shot site. Despite the unfavorable location with respect to the network, the availability of data at three stations, including numerous secondary arrivals, removes the necessity of incorporating azimuthal information to yield a stable location.

The location estimates for explosion 1 using the two S velocity models are listed in Table 4. The constant V_p/V_s model (Model A) yields vastly superior results, both in terms of the accuracy of location and the data fit. Even the origin time is well estimated. In contrast, in the case of Model B, the 18 by 10 km error ellipse does not even encompass the true location, and the origin time is 3 seconds early. The excellent fit for Model A is somewhat surprising. The existence of significant lateral heterogeneity in crustal thickness and P_n velocity in the region (Antonenko, 1984), combined with the location of the shot outside the network, would lead one to expect less favorable results. On the one hand, it is true that the DSS profile used for the P velocity model is located between the shot point and the network, so the P structure itself may be reasonably appropriate. On the other hand, we would have expected to obtain better results with Model B, which has an S structure that is consistent with both DSS and teleseismic receiver structure results.

Table 4

Calculated and true locations for chemical explosions, using velocity models A and B

Explosion	Model	O.T.	Latitude	Longitude	Error ellipse (km)	True error (km)	Mean residuals
1	True	0.30	50.281	72.172			
	A	0.65	50.263	72.161	5 x 3 @ -84°	1.8	0.08 s, 1.5°
	B	-2.65	50.342	71.815	18 x 10 @ -81°	40.1	0.79 s, 2.8°
2	True	5.00	50.000	77.333			
	A	5.23	50.029	77.257	2 x 1 @ +19°	8.7	0.24 s, 2.6°
	B	5.30	50.026	77.249	7 x 3 @ +20°	9.7	0.60 s, 2.9°
3	True	0.30	50.281	72.172			
	A	1.34	50.258	72.241	18 x 9 @ -73°	7.8	0.34 s, 9.9°
	B	-2.05	50.270	71.834	22 x 13 @ -90°	37.6	0.39 s, 11.0°

For comparison, we also show the location results for explosion 3 in Table 4. Despite the overlapping teleseism, the results are nearly identical to that for explosion 1. As before, only the estimated origin time is off significantly, over 1 second late for Model A and 2 seconds early for Model B. This 3 second difference in calculated origin time for the two velocity models also mirrors the result for explosion 1. In terms of the input data, the only differences are the absence of a measured P_n azimuth for station KKL, and the fact that the data from station KSU were obtained from a high-pass-filtered version of the seismogram. Perhaps the 1 second shift in fit to the origin time between explosions 1 and 3 is due to the masking of smaller amplitude initial arrivals by the interfering teleseism.

Explosion 2 was located within the network, at a distance range from stations BAY and KKL (about 150 km) such that the first seismic phases are crustal arrivals. Unfortunately, this removes the availability of P_n - P_g arrival differences as constraints for the location, and also probably makes the identification of the first S arrival somewhat less reliable. The separation between shot 2 and station KSU is comparable to that between shot 1 and stations BAY and KKL, so mantle refracted waves are the first arrivals and a secondary crustal P phase is again observed. Azimuthal data are included in the calculations, although they were not required to produce acceptable location estimates.

Table 4 contains the location results for chemical explosion 2 for the two crustal models. The two estimated locations are nearly identical: they are both shifted 9 km west of the true location, which falls outside the error ellipse in each case. Comparison of the observed and calculated travel times indicates that the P velocity model is too slow in the upper layers, causing

the shift in location towards stations BAY and KKL. The only major difference in the results for the two models is the S_n residual at KSU, which is about 1 second late for Model A but over 3 seconds late for Model B. This suggests that the S velocities in the deeper layers of Model B are systematically too high. This is consistent with the Model B results for explosion 1, for which the calculated S arrival times were significantly early.

Since most of the regional event locations are determined using data from only two stations (BAY and KKL), it is informative to test the two-station location capability on the chemical explosions. The locations were recalculated (using Model A) excluding the data from station KSU, with little or no significant effect on the results. In the case of explosion 1, the epicenter and origin time are essentially unchanged, although the error ellipse expands by 10%. For explosion 2, the epicenter shifts 2 km westward and the origin time is 0.25 seconds later. However, the error ellipse does enlarge significantly, to 8.5 by 1.5 km. Thus in these two cases where the true event locations are known, we can derive reasonable location estimates using data from only two stations. The success of this test gives us considerable confidence in the reliability of the regional event locations discussed below, which were mostly obtained using data from two stations.

Results for the JVE compared to locations from other sources are shown above in Table 5. The difficulty in identifying clear direct S arrivals in the JVE seismograms limited its usefulness for our purposes as a master event. However the regional location results are still quite good, especially compared to the teleseismic results based on many observations.

A major product of our location effort is a catalog of well-located regional events recorded by the NRDC network. Our published locations, with two typographical errors corrected, are presented in Table 6. These locations have been used by other scientists in their studies of wave propagation in the Kazakhstan region (Chan et al., 1990; Sereno, 1990).

We had two major successes in identifying sites of industrial explosions from SPOT satellite images (Thurber et al., 1989). One was for the area around the town of Ekibastuz, north of NRDC station Bayanaul, and the other was for an area just north of Lake Balkash, south of station Karkaralinsk. In both cases, temporal changes in the appearance of surface mining or quarrying sites were detectable, lending further credence to their identification as the sources of the observed seismic events. At the time of our search through the SPOT catalog, only three other scenes were available for areas in which events were provisionally located (events a, h, and j of Thurber et al. (1989)). Only one tentative identification of an explosions site could be made - event j might be associated with a mine or quarry site at 51° 50' N, 74° 20' E, located northwest of the town of Shiderty. It is possible that additional event sites could be identified, either now or in the future, if and when high-resolution satellite coverage (or maps) of the region become more available or more complete.

Table 5

Comparison of locations for the Joint Verification Experiment explosion in the USSR

Location source	Latitude	Longitude	Error	Uncertainty
Regional data	49.926	78.795	5 km	2 x 5 km
PDE	49.833	78.808	6 km	< 8 km
CSS	49.821	78.796	7 km	?
SPOT image	49.882	78.824	< 1 km	

Table 6

Catalog of 1987 two- and three-station event locations

ID	O.T. (d-h-m-s)		Latitude	Longitude	Error ellipse	Type	Area
a	1340936	16.4	50.190	74.157	26 x 3 @ -85°	blast	Karaganda
b	1350909	35.2	51.709	75.514	8 x 4 @ +74°	blast	Ekibastuz
c	1351035	0.3	49.304	72.712	3 x 2 @ +53°	blast	Karaganda
d	1410916	43.3	50.744	73.279	2 x 2 @ -80°	blast	Karaganda
e	1430849	22.7	49.275	75.738	5 x 2 @ -34°	blast	Karagayly
f	1450926	43.7	51.670	75.454	12 x 3 @ +84°	blast	Ekibastuz
g	1450956	40.9	51.743	75.316	10 x 2 @ +74°	blast	Ekibastuz
h	1460531	4.8	51.819	74.797	6 x 4 @ -85°	blast	Ekibastuz
i	1460833	26.5	51.760	75.571	15 x 6 @ -83°	blast	Ekibastuz
j	1621242	4.9	51.454	75.488	7 x 5 @ +16°	blast	Ekibastuz
k	1621250	34.3	51.677	75.525	17 x 7 @ +88°	blast	Ekibastuz
l	2340021	50.7	44.129	85.363	12 x 6 @ -69°	quake	Tien Shan
m	2390852	53.0	51.213	74.302	13 x 5 @ -26°	blast	Ekibastuz
n	2390938	34.8	46.900	77.389	6 x 3 @ +23°	blast	Balkash
o	2440344	38.8	43.808	85.948	6 x 5 @ +14°	quake	Tien Shan
p	2440908	52.0	46.924	77.241	14 x 5 @ +15°	blast	Balkash
q	2450802	10.2	51.639	75.481	12 x 6 @ -69°	blast	Ekibastuz

3. Conclusions and Recommendations

Starting with very little prior information, we have demonstrated the potential for a sparse seismic network of three 3-component stations, with an aperture of about 400 km, to locate events over a wide region with reasonable accuracy and precision, both for epicenter and depth. Some keys to the success of this effort have been:

(1) the initial availability of an adequate crustal model, coupled with the inferred modest level of lateral variations in crustal structure within the array;

(2) the availability of data from known sources (the 1987 chemical explosions) to aid the calibration of travel time models;

(3) the existence of identifiable secondary P arrivals;

(4) the availability of satellite imagery to confirm the source location of some events;

(5) the ability to pursue a multifaceted approach to the investigation of the overall location problem (empirical, theoretical, observational).

We can make several specific recommendations for future efforts related to regional event location:

(1) employ array studies to help identify and characterize secondary regional phases;

(2) use short time windows at the onset of the P arrival for precise azimuth estimation;

(3) obtain total coverage of the region in question by satellite imagery - including multiple sources of data (e.g., SPOT, LANDSAT).

Overall, we regard regional seismic event location to be a difficult but quite tractable problem.

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